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Aging and feature-binding in Visual Working Memory: The role of verbal rehearsal

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Forsberg.

**Abstract**

Age-related decline in ability to bind and remember conjunctions of features has been proposed as an explanation for the pronounced decline of visual Working Memory (WM) in healthy aging. However, evidence that older adults exhibit greater visual feature binding deficits than younger adults has been mixed. Binding deficits in older adults are often observed using paradigms with easy-to-label features. Labeling and rehearsing single features may result in apparent binding deficits if older adults rely on comparatively intact verbal memory to compensate for declining visual WM. This strategy would be more useful for single features (e.g., ‘red’), than for conjunctions of features (e.g., ‘red triangle’) which are more cumbersome to rehearse, and thus visual feature-binding paradigms which do not prevent verbal strategies may unintentionally measure verbal load differences. Across three experiments (total N = 150), we investigated the role of verbal rehearsal by manipulating ease of stimulus labeling for visually presented single features and conjunctions of two features.

Overall, visual memory for difficult-to-label, non-categorical, visual information appeared especially limited for older adults, likely because it impedes engagement of other systems, such as verbal WM or long-term memory. Therefore, comparing younger- and older-adult task performance may not straightforwardly reveal age-related visual WM decline, but instead reflect applications of different strategies that tap different cognitive mechanisms. We discuss implications for the feature-binding literature, and the wider visual WM literature.

*Keywords:* Visual working memory, Cognitive aging, Feature binding, Verbal rehearsal, Articulatory suppression.

# Aging and feature binding in visual working memory: The role of verbal rehearsal

Working memory (WM) refers to cognitive functions that support the ready availability of a small amount of information on a temporary basis while undertaking ongoing actions and mental activities (e.g., Logie & Cowan, 2015). Along with other aspects of cognition, WM has been shown to be poorer in groups of older than in groups of younger healthy adults (e.g., Babcock & Salthouse, 1990; Bowles & Salthouse, 2003; Craik, Luo, & Sakuta, 2010; Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Johnson, Logie, & Brockmole, 2010; Park, Lautenschlager, Hedden, Davidson, & Smith, 2002). This age-related decline has practical importance because WM is believed to underpin effective operation of other cognitive functions, such as perception and problem-solving (e.g., Ma, Husain, & Bays, 2014), and to be related to general intelligence (e.g., Unsworth, Fukuda, Awh, & Vogel, 2014) and reasoning ability (e.g., Conway, Kane, & Engle, 2003; Kyllonen & Christal, 1990). The ability to retain visual features of stimuli in working memory appears to be particularly sensitive to age-related cognitive decline (e.g., Bowles & Salthouse, 2003; Gazzaley et al., 2005; Johnson et al., 2010). Two potential components of age-related decline in visual working memory have been proposed: First, reduction in the number of items that can be stored, and second, decreased ability to retain associations (*bindings*) between different object features (Bopp & Verhaeghen, 2009; Brockmole, Parra, Sala, & Logie, 2008; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Mitchell, Johnson, Raye, & D'Esposito, 2000b; Olson et al., 2004; Parra, Abrahams, Logie, & Sala, 2009; Sander, Werkle-Bergner, & Lindenberger, 2011). This distinction has been useful for understanding the marked decline of episodic memory with age (for a review, see Shing et al., 2010), where *associative deficits* (impairments when required to remember associations between items over and above any deficit exhibited for those items individually) have been demonstrated across a variety of

1 stimuli (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003; Spencer  
2 & Raz, 1995; see Old & Naveh-Benjamin, 2008 for a review and meta-analysis). However,  
3 the role of age-related deficits in temporary binding in visual working memory appears less  
4 straightforward: some experiments have reported age-related binding deficits and others not,  
5 and paradigm differences might have influenced these discrepancies.

6 Typically, memory for such short-term feature-bindings has been measured  
7 experimentally by comparing temporary memory for specific features, such as color, shape or  
8 location, individually or bound together (e.g., a colored shape in a particular location in an  
9 array). In these experiments, the same small sets of features are presented repeatedly in  
10 different combinations from trial to trial. For example, on one trial participants might be  
11 asked to remember a briefly presented array comprising a green circle, a red square and a  
12 blue triangle with the test of memory one or two seconds later. On the next trial, the memory  
13 array would consist of different combinations of colors and shapes. Variations of this general  
14 paradigm have been used extensively in the study of object perception and attention (e.g., Hu,  
15 Allen, Baddeley, & Hitch, 2016; Tas, Luck, & Hollingworth, 2016; for reviews of earlier  
16 research see Zimmer, Mecklinger, & Lindenberger, 2006), and in the study of the impact of  
17 age on working memory for visual features (e.g., Brockmole & Logie, 2013; Brown, Niven,  
18 Logie, Rhodes, & Allen, 2016; Cowan et al., 2006; Kessels, Hobbel, & Postma, 2007;  
19 Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000a; Rhodes, Parra, & Logie, 2016).  
20 Several studies have observed that while short-term memory for individual colors and shapes  
21 (and sometimes locations) was relatively preserved in older adults, it was significantly  
22 impaired for combinations of colors, shapes and locations (i.e., bindings) compared with  
23 younger adults (Mitchell et al., 2000a; Mitchell et al., 2000b; Brockmole & Logie, 2013;  
24 Kessels, Hobbel, & Postma, 2007; Chalfonte & Johnson, 1996). In contrast, other studies  
25 have reported no evidence for age-related binding deficits (e.g., Brockmole, Parra, Della Sala,

1 & Logie, 2008; Brown et al., 2016; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006;  
2 Parra, Abrahams, Fabi, Logie, Luzzi, & Della Sala, 2009a; Parra, Abrahams, Logie, & Della  
3 Sala, 2009b; Rhodes et al., 2016; for a review see Allen, Brown, & Niven, 2013). Feature-  
4 binding deficits are of practical importance for pathological aging, since simple visual WM  
5 binding tasks have distinguished pathological cognitive decline from that associated with  
6 healthy aging. Specifically temporary color-shape binding has been found to be unimpaired  
7 in healthy older people, but specifically impaired in individuals suffering from Alzheimer's  
8 disease (e.g., Parra et al., 2009a; Parra, Della Sala, Abrahams, Logie, Méndez, & Lopera,  
9 2011). Moreover, memory for temporary bindings between colors and shapes were found to  
10 be impaired in people with genetic mutations that result in early-onset Alzheimer's disease,  
11 when these individuals were otherwise asymptomatic and up to ten years before they would  
12 be expected to develop the disease (Parra, Abrahams, Logie, Méndez, Lopera, & Della Sala,  
13 2010). However, debate about which type of paradigm best distinguishes healthy from  
14 pathological aging has emerged due to recent inconsistent observations regarding whether or  
15 not there are age-related binding deficits in the WM literature (see Liang et al., 2016; Logie,  
16 Parra, & Della Sala, 2016; Parra et al., 2016).

17 In this paper, we identify and test a potential reason behind these inconsistencies: the  
18 studies reporting age-related binding deficits included common, easy-to-label stimuli (e.g.,  
19 common shapes like triangles, or colors like red) and did not attempt to prevent verbal  
20 rehearsal. In contrast, the studies where older adults did not show greater binding deficits  
21 were designed to reduce opportunities for verbal strategy use, by including difficult-to-label  
22 features (e.g., irregular hexagons or complex fractals) or requiring articulatory suppression,  
23 which requires participants to repeat an irrelevant pair of digits or short word aloud while  
24 viewing the stimulus arrays and until responding. See Table 1 for a summary of different  
25 paradigms (and stimulus types) used to measure age-related feature-binding deficits. One of

the largest studies on age-related deficits, including over 55,000 online participants, used features that could easily be labelled, and observed a significant age-related feature-binding deficit with age as a continuous variable (Brockmole & Logie, 2013), and with memory tested by reconstruction of the feature combinations. Similarly, Kessels, Hobbel, and Postma (2007) observed a binding deficit in older adults with stimuli consisting of easy-to-label objects presented in a grid for 3 seconds, requiring an immediate response, using reconstruction. Also, more recently developed delayed-estimation precision paradigms used to study binding also rely on a reconstructive procedure (Peich, Husain, & Bays, 2013; Pertzov, Heider, Liang, & Husain, 2015). The recent increase in the use of reconstructive paradigms and the size of the study by Brockmole and Logie (2013) both motivated the use of a reconstruction binding paradigm in the present study. The method used to quantify binding likely contributes to discrepancies regarding age-related binding deficits. However, we did not directly compare different types of binding paradigms, but focused instead on the effect of permitting verbalization in one paradigm (reconstruction).

Indeed, most memoranda – in memory experiments as well as in everyday life – can be remembered either via verbal codes or visual memory traces, or both (Lewis-Peacock, Drysdale, & Postle, 2014; Morey & Cowan, 2004). For example, remembering which glass was yours after putting it down at a party could be achieved using a verbal description (“the champagne flute”), as well as a visual representation of what the specific glass looked like. Such translation of visual representations into verbal code has been found to improve visual memory performance in younger adults (Brown, Forbes, & McConnell, 2006; Souza & Skóra, 2017). Despite this, tasks are often assumed to measure either visual or verbal WM, perhaps incorrectly (e.g., Logie, 2018). For example, Saito, Logie, Morita, & Law (2008) showed that participants used both visual and verbal codes to retain visually presented letter and word sequences (see also Logie, Saito, Morita, Varma, & Norris, 2016;. When a visual

stimulus is translated into a verbal code it can be maintained in memory via *sub-vocal rehearsal*, i.e., silent repetition of verbal labels for material to be recalled (see Logie, Della Sala, Laiacona, Chalmers, & Wynn, 1996; Wang, Logie, & Jarrold, 2016). Sub-vocal rehearsal is an essential feature of the ‘phonological loop’ (Baddeley, 1986, 1992; Baddeley, Lewis, & Vallar, 1984 ), part of the multi-component model of working memory (Baddeley & Hitch, 1974; Baddeley, 1986; Baddeley & Logie, 1999). While other conceptualizations of WM do not emphasize domain-specific stores, sub-vocal rehearsal of verbal material is generally recognized as a separate mechanism (Cowan, 1992; 2005; Oberauer, 2013, Camos, Lagner, & Barrouillet, 2009), while the presence of a visuospatial rehearsal mechanism is more contentious (see Hanley & Young, 2018; Logie, 2003; Logie et al., 2016; Morey, 2018).

Verbal rehearsal could be problematic in paradigms used to measure visual feature-binding, because such rehearsal is likely comparatively more effective for recalling single features (which requires maintaining, for example, three or four shapes in memory), than bound features (which requires rehearsing six or eight features, and crucially, which of them belong together). Moreover, the time available for rehearsal is typically limited, and is the same for single and binding trials. Therefore, if older adults have a greater tendency to employ verbal rehearsal and do so more successfully with single features, this could create an apparent age-related binding deficit – i.e., relatively preserved performance on single-feature than on binding trials, when statistically compared with the difference between single and binding trials in younger adults – in paradigms which allow verbal rehearsal.

The proposal that older adults may rely more on verbal rehearsal is supported by the broader research literature on cognitive aging, which suggests that not all cognitive functions decline with age to the same degree (for reviews see Logie & Morris, 2014; Perfect & Maylor, 2000). For instance, healthy older adults appear to have relatively spared verbal working memory. Studies (e.g., Johnson et al., 2010) and meta-analyses (e.g., Jenkins,



Myerson, Joerding, & Hale, 2000) have indicated that visuospatial cognition declines more with aging than does verbal cognition. In particular, working memory deficits for visuospatial material have been shown to be more severe in older participants than those for verbal material (e.g., Jenkins, Myerson, Hale, & Fry, 1999; Leonards, Ibanez, & Giannakopoulos, 2002; Myerson, Hale, Rhee, & Jenkins, 1999, but see Park et al., 2002; Salthouse, 1995). In general, in tasks that permit verbal rehearsal (e.g., digit span tasks) older adults are often observed performing as well as younger adults (Fisk & Warr, 1996), whereas age differences are large for visual material (e.g., remembering visual patterns; Johnson et al., 2010).

Furthermore, in an online study with over 95,000 participants aged 18 to 90 performing a variety of memory tasks, Johnson et al. (2010) found that the factor structures of performance on various WM tasks varied among age groups. In other words, the relative magnitudes of shared variance among the tasks differed for different age groups. Visual-pattern memory was more correlated with performance on the other measures among the older participants than among the younger participants. Hence, for the older participants, visual pattern memory seemed more related to some general cognitive capacity, but in younger people, it seemed to reflect a specific capacity. The opposite was found for verbal memory, measured by memory for number sequences (digit span). This could suggest that older adults are compensating for decline in function, for instance in brain regions supporting specific visuospatial WM subsystems, by making greater use of verbal strategies (Reuter-Lorenz et al., 2000). For instance, when faced with a visual memory task, they might attempt to support their impaired visual memory ability by applying verbal labels to the visually presented materials and use their relatively intact verbal memory abilities to rehearse those verbal labels, thereby performing better than if they had relied on their visual memory abilities alone. Indeed, some evidence suggests that older adults – despite capacity deficits – can use strategies (such as focusing on a subset of important information) as successfully as

1 younger adults in both the verbal (e.g., Castel, Benjamin, Craik, & Watkins, 2002) and  
2 visuospatial (e.g., Siegel & Castel, 2018) memory domains. However, other research suggests  
3 that younger adults are more likely than older adults to engage in verbal rehearsal to improve  
4 WM performance (e.g., Peterson & Naveh-Benjamin, 2016), and may be more likely than  
5 older adults to initiate strategies to support long-term memory (see Craik & Rose, 2012).  
6 Despite this, to the extent that older adults become (at least subconsciously) aware of failing  
7 visual memory relative to verbal, they may be particularly likely to supplement visual  
8 memory with verbal strategies, thus offsetting the general tendency of younger adults to do so  
9 more readily under certain conditions. Identifying strategies people use to maintain daily  
10 function in old age is essential to understanding cognitive decline, and how to measure it  
11 experimentally as well as clinically. If older adults' performance is more negatively affected  
12 than younger adults when verbal rehearsal is prevented – compared to circumstances where it  
13 is allowed – this would suggest that a greater proportion of older adults' successful 'visual'  
14 WM memory is supported by verbal rehearsal. This proposed instance of how a relatively  
15 intact capacity may be recruited to compensate for a declining one has potential implications  
16 for numerous paradigms used to investigate memory decline across the lifespan. Successful  
17 compensatory use of verbal rehearsal strategies by older adults could inform understanding of  
18 general circumstances which may alleviate older adults' decline on tasks that are assumed to  
19 involve visual memory.

20 In three experiments we manipulated the likelihood of verbal rehearsal by  
21 manipulating stimulus labeling difficulty to test whether older adults show relatively better  
22 performance for easy-to-label stimuli, compared to difficult-to-label stimuli (presumed to be  
23 more cumbersome to rehearse verbally). We also used articulatory suppression to test  
24 whether performance gains for easy-to-label stimuli could be attributed to verbal rehearsal.  
25 Considering evidence of relatively spared verbal WM memory with age, we hypothesized

that older adults would perform more similarly to younger adults when items were easier to label, but show an age-related decline for difficult-to-label materials, which are difficult to rehearse verbally. Secondly, binding deficits are typically quantified by comparing mean performance on single-feature trials with that on binding trials. If participants approach visual feature-binding tasks verbally, the crucial comparison between memory for single and bound features can be thought of as a (verbal) load manipulation, requiring twice as many items in the binding condition. This should impede both development of effective labels and ability to rehearse them. Because successful verbal rehearsal hinges on having sufficient time to rehearse the to-be-remembered words, such a strategy should be suitable for rehearsing three or four single features for a couple of seconds, but not be as useful when asked to retain twice the number of features in the binding condition. Therefore, we hypothesized that the opportunity for verbalization would produce age-related apparent feature-binding deficits by enabling older adults to perform well in the single-feature condition but being much less helpful in the binding condition. This could explain discrepancies in the literature, as outlined above.

### **Experiment 1**

In Experiment 1 we investigated whether making verbal labeling difficult resulted in the appearance of a greater age-related decline in temporary memory for visual features. Recall was tested using a reconstruction procedure in which participants responded by selecting features from arrays of individual features. We presented some stimuli to which it was easy to assign verbal labels, and others for which it was more difficult, measuring Shape and Color Recall separately, similar to Experiment 3 in Brockmole et al. (2008). For some trials, participants remembered only single features (either colors or shapes), and for the other

1 trials, they remembered bound features (integrated objects consisting of a shape of some  
2 color). We hypothesized that when task features were easy to label older adults would  
3 perform similarly to younger adults in single-feature conditions, but perform more poorly  
4 than younger adults when asked to remember bound features, i.e., an age-related feature-  
5 binding deficit (in line with Brockmole & Logie, 2013). In contrast, when features were  
6 difficult to label, we anticipated that verbal rehearsal would be less feasible and all  
7 participants would rely on retaining visual representations rather than verbal labels. Thus we  
8 did not expect an age-related deficit for bound, as compared to individual features, consistent  
9 with previous studies where verbal rehearsal was prevented (Parra et al., 2009; Rhodes, Parra,  
10 & Logie, 2016).

## 12 **Methods**

13 **Participants.** We recruited 51 participants, all native speakers of English. Twenty-  
14 five University of Edinburgh students (three male and one participant who did not identify as  
15 either male or female) aged 18 – 27 ( $M = 22.3$ ,  $SD = 2.1$ ) years received £8.50 in return for  
16 participation. Twenty-six older adults (six male), all from the University of Edinburgh  
17 psychology research community volunteer panel, aged 66 – 75 ( $M = 69.7$ ,  $SD = 2.8$ ) years,  
18 were each given £10 in return for participation. One older adult was excluded for not  
19 completing the memory task. The final sample size of 50 participants was determined prior to  
20 data collection, based on recent studies' sample sizes addressing similar questions (e.g.,  
21 Rhodes, Parra, & Logie, 2016; Rhodes, Parra, Cowan, & Logie, 2017; Brown & Brockmole,  
22 2010). Years of education did not differ significantly between the age groups (older:  $M =$   
23  $15.0$ ,  $SD = 3.7$ ; younger:  $M = 16.2$ ,  $SD = 1.6$ );  $t(32.27) = 1.40$ ,  $p = .170$ ,  $d = 0.41$ . Providing  
24 years of education was optional, and was given by 20 younger adults, and 24 older adults.

Prior to participating in the main experiment, all participants completed an on-screen version of the Dvorine pseudo-isochromatic plates (Dvorine, 1963) to assess color-vision. More than five errors are indicative of color-vision deficits (Dvorine, 1963), and no one was excluded on this basis. All older adults scored 86 or above ( $M = 96.7$ ,  $SD = 3.2$ ) on Addenbrooke's Cognitive Examination (ACE-III; Hodges, 2012), completed at the very end of their session only. A score lower than 82 is considered indicative of cognitive impairments (Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006). After completing the memory task, participants were asked to name each stimulus twice by typing it in a computerized naming survey, for a measure of 'Label-ability' and word-length in easy- and difficult-to-label stimuli. All participants completed the National Adult Reading Test (NART; Nelson, 1982) for an estimate of verbal IQ. Estimated verbal IQ scores were significantly higher in the older adult group ( $M = 123.9$ ,  $SD = 4.1$ ) than the younger adult group ( $M = 118.3$ ,  $SD = 4.1$ ),  $t(47.9) = 4.69$ ,  $p < .001$ ,  $d = 0.37$ .<sup>1</sup> The study was approved by our local Ethics Committee.

**Stimulus and Apparatus.** We established relative ease of labeling of visual features by asking 15 participants (aged  $M = 25.0$ ,  $SD = 5.9$ , range 19 to 42 years, 5 male) who did not take part in the main experiment to name each color or shape three times (see Supplementary Material). This guided our selection of 32 features. The easy-to-label stimuli were shapes such as triangles and squares, and prototype versions of common colors such as red and green. The other stimuli were more difficult to label, such as irregularly-sided shapes and blends of common prototype colors. The eight difficult-to-label shapes were identical to those used by Brockmole et al. (2008) and by Rhodes, Parra, Cowan, and Logie (2017). To select these items, we considered features difficult to label if a) many participants failed to generate labels for them, b) labels for the same feature were not consistent among and within

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<sup>1</sup> Cohen's  $d$  was calculated using the population level Standard Deviation for IQ ( $SD = 15$ ) for this and all subsequent Verbal IQ comparisons.

participants, and c) verbal labels were longer, such as combinations of two color labels (e.g., ‘greenish-yellow’), presumably making such verbal labels more difficult to rehearse successfully within the experimental time frame (consistent with Baddeley, Thomson, & Buchanan, 1975, word-length effect).

Easy-to-label features were those that generated the same, single-word label consistently among and within the 15 participants<sup>2</sup>. The two complete sets of shapes and the color RGB values are given in the supplementary material. Difficult-to-label stimuli were defined as such relative to the easy-to-label stimuli, but they were not impossible to label, as participants could creatively label uncommon colors and shapes. We asked participants to name all items after completing the memory task, so that we could compare ‘label-ability’ and word-length in easy- and difficult-to-label stimuli.

For each trial, three or four memory items were presented on the computer screen with a grey background, randomly in eight possible locations around an invisible circle, 4.5 cm from the center of the screen. We combined item colors and shapes randomly without replacement, with the restriction that all features in each trial were either easy or difficult to label. Each stimulus image was about 2.2 cm<sup>2</sup> (visual angle approximately 2.10°) and viewing distance was approximately 60 cm. Stimuli were presented using PsychoPy v1.82.01 (Peirce, 2007) and displayed on a 22" LCD Monitor, with a diagonal of 20.6", and a screen resolution of 1680 × 1050.

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<sup>2</sup> The final set of easy-to-label colors was named by 100% of surveyed pilot participants with 90% within-participant consistency (average word length 5.4 letters). Difficult-to-label colors were named in 87.2% of instances, with within-participant consistency of 39.2% (average word length 7.6 letters). Easy-to-label shapes were named in 99.8% of instances with 91.9% within-participant consistency (average word length 7.2 letters). Difficult-to-label shapes were named by 54.3%, within-participant consistency 45.5% (average word length 12.1 letters).

**Design and Procedure.** An example of the memory task procedure is shown in Figure 1. Participants indicated recalled colors and shapes with mouse clicks. The experiment consisted of two single- and two dual-feature blocks. One block tested memory for color only (each test object was a ‘blob’ of a single color), one for shape only (all objects were black), and two blocks tested memory for both, with these blocks differing in which response (i.e., color or shape) was required first. We used color blobs and black shapes for our single-feature conditions rather than colored shapes to prevent participants from automatically encoding both features of the objects even when the task was to remember just one feature, based on evidence suggesting that color encoding is automatic (Ecker, Maybery, & Zimmer, 2013). We randomized block order across participants.

In each trial, participants viewed the test array (1500 ms), then there was a delay (2150 ms), and then probe circles outlined in dark grey appeared in all positions occupied by studied items (1500 ms) to offer contextual support for memory (see Figure 1). To indicate the randomly selected object to be remembered, one of these probe circles was filled in dark grey. Thereafter, the participant was asked to mouse-click the probed object’s originally-displayed color and/or shape from a range of 16 shapes and 16 colors on the screen. The response screens consisted of all the 16 colors (eight easy-to-label and eight difficult-to-label) or 16 shapes (eight easy-to-label and eight difficult-to-label), probing color or shape memory, respectively, as illustrated in Figure 1. The presentation position for each color or shape was the same throughout the whole experiment for each individual participant but varied randomly among participants. This was to facilitate responses and minimize time spent searching for a specific color or shape to make responses. Set size varied randomly across trials, such that each trial presented either three or four items, selected based on previous studies indicating that three to four items generate performance levels below ceiling and above chance (Cowan, 2010; Luck & Vogel, 1997). We included two different set sizes as a

precaution against floor or ceiling performance within age groups and/or conditions. Within each block, each participant completed 17 trials for each combination of set size and stimulus label-ability, resulting in a total of 68 trials per block, and a total of 272 trials<sup>3</sup>. Trial numbers were selected to ensure a practically reasonable session length (the full task took up to 65 minutes to complete).

**Analysis.** To analyze the data, we used a model comparison approach based on Bayes factors, also used by Rhodes et al. (2016; see also, Brown et al., 2016; Rhodes et al., 2017), implemented with the BayesFactor package in *R* (see Morey, Rouder, & Jamil, 2015 and R Core Team, 2015). Bayesian statistics arguably provide a better foundation for probabilistic inference than null hypothesis significance testing (Kruschke, 2011; Raftery, 1995; Wagenmakers, 2007). In our implementation, Bayes factors ( $B$ ) reflect the weight of evidence in favor of omitting a particular component from a model containing all relevant available variables. We used the default settings of the *anovaBF* function (*R*; the BayesFactor package), with the modification that ‘whichModels’ was set to ‘top’, to compare linear versions of the full model ( $M_f$ ), including all main effects and interactions, with each different model in which a given experimental parameter was omitted ( $M_1$ ). The *anovaBF* function was used with its default settings (“medium” prior scale for fixed effects, and “nuisance” prior scale for the random effect); as recommended by Rouder, Morey, Speckman, and Province (2012) to obtain Bayes factors. This family of priors was designed to be invariant with respect to linear transformations of measurement units as well as general and broadly applicable (Rouder et al., 2012), and found to be more conservative than conventional ANOVAs (Rouder et al., 2009; Wetzels et al., 2011), and is commonly considered suitable for Bayesian ANOVAs in working memory research (e.g., Oberauer &

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<sup>3</sup> Except two younger participants who did a shorter version of 56 trials, in total 224 trials, due to a computer error.



Eichenberger, 2013; Rhodes et al., 2017). We specified 50,000 MCMC iterations<sup>4</sup>, and we ran an additional 10,000 iterations until the proportional error associated with each Bayes factor was less than 5%, similar to Rhodes et al. (2016).

The *anovaBF* function quantifies the strength of evidence  $B$  in favor of a reduced model ( $M_1$ ) relative to the comparison full model ( $M_f$ ) in light of the data, returning the Bayesian likelihood ratio of  $M_1$  and  $M_f$ . In our analyses, the output is interpreted as follows: the observed data is  $B$  times more likely under the reduced model ( $M_1$ ) than under the full model ( $M_f$ ). So,  $B < 1$  indicates evidence that an omitted parameter was important, while  $B > 1$  indicates evidence it was not.  $B$  can range from 0: indicating overwhelming support for the full model that includes the parameter ( $M_f$ ), to 1: indicating equal support for both models, to infinity: providing overwhelming support for the reduced model that omits the parameter ( $M_1$ ; Dienes, 2012). By symmetry,  $1/B$  provides evidence for retaining the parameter in the model.

Bayes factors cannot conclusively be interpreted using threshold cut-off points; subjective judgmental interpretation is necessary. Typically,  $B = 1$  is considered ‘no evidence’,  $B$  between 1 and 3 is considered ‘anecdotal’ (Wetzels & Wagenmakers, 2012) or ‘not worth more than a bare mention’ (Jeffreys, 1961),  $B$  greater than 3 is considered ‘substantial’, between 10 and 30 ‘strong’, 30 – 100 ‘very strong’, and over 100 ‘decisive’ evidence (Jeffreys, 1961; Wetzels & Wagenmakers, 2012). Symmetrically, if  $B$  is less than 0.33, we may consider the evidence against including its parameter to be at least ‘substantial’.

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<sup>4</sup> Markov chain Monte Carlo iterations (MCMC) is a stochastic simulation technique commonly used to compute inferential quantities (see Green, 1995; Han & Carlin, 2001), and used to integrate the likelihood with respect to the priors on parameters to compute Bayes factors.

However, these labels are subjective (see Morey, 2015), so we apply them only tentatively and urge readers to evaluate the strength of evidence provided by the  $B$  values for themselves.

## Results

We analyzed Color and Shape Recall separately. In both analyses, the full Bayesian ANOVA model included main effects of Age (young vs. old), Trial Type (single feature vs. binding) and Label-Ability (easy-to-label vs. difficult-to-label) and all possible interactions between these main effects. Recall accuracy was the dependent variable. Note that binding trials required reproduction of an item's color *and* shape. Thus, a color binding trial tested memory for colors while the participant was also required to remember the shape (see Figure 1).<sup>5</sup> To reduce error due to participant attentional lapses, we excluded trials with reaction times over 10 seconds from all analyses (color trials: 1.46% excluded from the younger adults, 1.44% from the older. Shape: 2.06% excluded from the young, 4.53% from the older).

In the color analysis, the main effect of trial type was obtained by comparing color-only trials with color-and-shape trials where color was probed first (i.e., the binding condition). The Color Recall accuracies for younger and older adults for more and less easy-to-label stimuli in the different conditions are presented in Table 2. See Supplementary Materials for Mean values,  $SD$ s and Cohen's  $d$  for all main effects. The younger participants performed better than the older (proportion correct younger:  $M = .82$ ,  $SD = .27$ , older:  $M = .68$ ,  $SD = .33$ ), and our analysis indicated strong evidence in favor of retaining age group in the model ( $1/B = 31.59$ ). Easy-to-label colors ( $M = .85$ ;  $SD = .25$ ) were remembered better than difficult-to-label ( $M = .64$ ,  $SD = .34$ ), and the evidence for retaining stimulus Label-

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<sup>5</sup> We did not include the secondary feature (e.g., the shape in the color binding condition) in our quantification of binding to ensure that older adults were not disadvantaged if they took longer to reproduce the first feature. The average accuracy for the secondary features (see Supplementary Materials) suggested that participants generally attempted to remember both features.

Ability in the model could be considered ‘decisive’ ( $1/B = 2.5 \times 10^{98}$ ). Overall memory for color only ( $M = .80$ ,  $SD = .28$ ) was better than in the binding condition when Shape Recall was also required ( $M = .70$ ,  $SD = .32$ ), ( $1/B = 1.4 \times 10^{21}$ ). Overall, the evidence did not indicate an age-related binding deficit; i.e., the *difference* in memory accuracy for color only and color when shape was also remembered did not differ between the age groups ( $1/B = 0.31$ ). Moreover, we found no evidence for an overall Trial Type  $\times$  Label-Ability interaction ( $1/B = 0.25$ ). However, we observed a larger performance drop between easy-to-label and difficult-to-label colors for older adults than younger ( $1/B = 2.3 \times 10^6$ ), which differed between single and binding trials (evidence for keeping the Age  $\times$  Trial Type  $\times$  Label-Ability interaction in the model:  $1/B = 12.82$ ), see Figure 2. In other words, the difference in accuracy between easy- and difficult-to-label trials was greater for the older adults than the younger. Furthermore, this interaction was modulated by trial type (i.e., single- feature or binding). The difference in differences in old and young was greater in the single-feature condition because the groups performed similarly in the easy-to-label color-only condition.

We conducted similar analyses with Shape Recall as the dependent variable (see Table 3 for mean accuracies across age groups and experimental conditions). We found evidence in favor of a performance difference between younger ( $M = .76$ ,  $SD = .30$ ) and older ( $M = .57$ ,  $SD = .35$ ) participants ( $1/B = 299.13$ ), and memory for easy-to-label shapes ( $M = .74$ ,  $SD = .31$ ) was better than for difficult-to-label shapes ( $M = .59$ ,  $SD = .35$ ,  $1/B = 3.6 \times 10^{47}$ ). There was also ‘decisive’ evidence that overall memory accuracy was better in the single-feature condition (shape only;  $M = .73$ ,  $SD = .31$ ), than in the binding condition ( $M = .60$ ,  $SD = .35$ ;  $1/B = 5.5 \times 10^{30}$ ), but no evidence for a binding deficit in older adults (no evidence for keeping the Trial Type  $\times$  Age Group interaction in the model:  $1/B = 0.90$ ). There was strong evidence for keeping the interaction between Label-Ability and trial type in the model ( $1/B = 24.7$ ), but no evidence in favor of an Age-Group  $\times$  Label-Ability interaction

( $1/B = 0.11$ ), nor was this modified by trial type (evidence of retaining Age Group  $\times$  Label-Ability  $\times$  Trial Type interaction in the model;  $1/B = 0.054$ ). See Tables 6 and 7 for the complete outputs of the Bayes Factor analyses.

The results of the naming survey completed after the memory task confirmed that participants were able to name easy-to-label colors and shapes more often than difficult-to-label ones, and for named items, difficult-to-label items were described using more characters. See Supplementary Materials for details about these analyses. We also report the proportion of ‘in-array errors’ by condition (i.e. how often participants incorrectly selected an un-probed item from the original memory array) and information about memory for shapes when colors were probed first (included to verify that participants tried to remember both features in the binding condition), for all experiments, in the Supplementary Materials.

## Discussion

Overall, younger adults performed better than older, and memory for easy-to-label items was better than for difficult-to-label items, both for colors and shapes. For Color Recall, our analysis indicated that older adults’ performance was relatively preserved for easy-to-label colors and that the *difference* in accuracy between easy- and difficult-to-label stimuli was greater in older adults than in younger (see Figure 2.). This was consistent with our hypothesis that older adults may depend more on sub-vocal rehearsal of verbal labels to remember colors than their younger counterparts, as suggested by Logie et al. (2015). Crucially, this older-adult ‘label-ability boost’ was substantially larger for the single feature condition than the binding condition, consistent with the proposal that our experimental time frame (3650 ms from item disappearance to response request) was suitable to rehearse three or four color labels, but too short to rehearse six or eight features to remember the bound objects successfully.

1           These observations were consistent with our proposal that use of verbal strategy can  
2 'mask' decline in visual single-feature WM in healthy older adults quite efficiently when  
3 colors are easy to label, and the number of features is small (three to four). Hence, studies  
4 using this paradigm could find evidence for and against an age-related feature-binding deficit  
5 depending on whether the stimuli were easy or difficult to label, respectively. Indeed, we  
6 would have interpreted the significantly greater gap between memory accuracy for single-  
7 and dual-feature trials observed for the older adults compared to the younger adults in our  
8 color trials as evidence for feature-binding deficits in the older adults had we not included the  
9 difficult-to-label color condition.

10           However, it is possible that older adults were especially good at remembering the  
11 easy-to-label colors in the single-feature condition because the colors were familiar or easily  
12 distinguishable, rather than because they could be labeled and rehearsed. Color familiarity,  
13 label-ability, and distinctiveness are inherently entangled because as any language evolves  
14 more common, salient colors are more likely to receive linguistic labels. To test this  
15 alternative explanation and investigate the role of sub-vocal rehearsal directly, we applied  
16 articulatory suppression in Experiment 2. Suppression requires participants to repeat  
17 irrelevant phonemes aloud throughout task performance and is thought to prevent sub-vocal  
18 rehearsal (e.g., Baddeley, Lewis, & Vallar, 1984; Murray, 1965).

19           However, we did not find an interaction between stimulus label-ability and age  
20 group for shape memory. This attenuated support for our hypothesis that older adults rely  
21 more or more successfully on verbal strategies to remember visual stimuli, as it is unclear  
22 why older adults would benefit from verbal labels in remembering colors but not shapes.  
23 Memory failure may result from failure during encoding, maintenance during the inter-  
24 stimulus interval, or failure to respond – or some combination of these (Mitchell et al.,  
25 2000a). It is possible that the colors were more visually discriminable than the shapes during

the encoding stage. Indeed, studies examining early, low-level visual processing in younger adults have suggested that color is salient in the pre-recognition stage (Callaghan, 1984; Cavanagh, 1987; Troscianko & Harris, 1988), and that colored objects are recognized faster than monochrome objects (Humphrey, Goodale, Jakobson, & Servos; 1994, Wurm, Legge, Isenberg, & Luebker, 1993). It is therefore possible that presentation time in this experiment (1500 ms) was insufficient to allow older adults in particular to encode and label the shapes in a way that facilitated recall, thus preventing them from benefitting from sub-vocal rehearsal during the maintenance phase. We addressed this possibility in Experiment 3.

## Experiment 2

To investigate whether the observed age differences for color memory in Experiment 1 were due to the sub-vocal rehearsal of verbal labels, in Experiment 2 we applied suppression to half the trials, using the reconstruction paradigm of Experiment 1. We hypothesized that if reliance on sub-vocal rehearsal enabled the older adults' memory 'boost' for easy-to-label colors in the single-feature condition, suppression should reduce performance in that condition but not affect performance in the other conditions, especially not for the difficult-to-label colors, where we do not expect performance to rely on sub-vocal rehearsal. Alternatively, if the boost was not due to sub-vocal rehearsal, but because the easy-to-label, common colors were more salient – or more clearly and accessibly encoded in long-term memory – the older adults' performance boost should still be observed during suppression. Memory for color was the only dependent variable in this experiment.

## Methods

**Participants.** We recruited 52 new participants in the same way as in Experiment 1, specifying that they not have taken part in that earlier experiment. They included 25 younger adults (8 female) aged 18 – 25 ( $M = 21.5$ ,  $SD = 2.0$ ) years, and 27 older adults (10 male), aged 63 – 76 ( $M = 70.0$ ,  $SD = 4.7$ ) years. Two older adults were excluded due to color vision error scores over the cut-off point of 5 errors (6 and 13 errors, respectively). Years of education did not differ significantly between the groups (older adults:  $M = 14.8$ ,  $SD = 3.6$ , younger adults:  $M = 15.5$ ,  $SD = 1.7$  years,  $t(33.8) = .92$ ,  $p = .37$ ,  $d = 0.25$ ). Providing years of education was optional,  $N = 20$  for the younger adults,  $N = 24$  for the older. All older adults scored above the recommended cut-off score indicating potential cognitive impairment of 25 on the ACE-III mini-score (Hsieh et al., 2015;  $M = 28.7$ ,  $SD = 1.1$ ), completed at the very end of the testing session NART-predicted verbal IQ scores were significantly higher in the older group ( $M = 123.7$ ,  $SD = 3.3$ ) than the younger group ( $M = 115.7$ ,  $SD = 3.7$ ),  $t(48) = 8.15$ ,  $p < .001$ ,  $d = 0.53$ . The study was approved by our local Ethics Committee.

**Stimulus and Apparatus.** The stimuli were identical to those used in Experiment 1, displayed using the same equipment.

**Design and Procedure.** The procedure was identical to that used in Experiment 1, with the following modifications. The four blocks were: 1. Color-only, 2. Color-only with Suppression, 3. Binding, 4. Binding with Suppression. Since the Suppression manipulation adds time and can be tiring, the total number of trials was reduced to 60 trials per block, resulting in a total of 240 trials. Suppression started prior to the encoding of items and continued throughout the encoding and testing phases, to minimize the use of verbal strategies as much as possible. Participants initiated each trial by pressing the space bar. We instructed participants that at the start of each suppression trial two randomly generated digits

would be displayed in the center of the screen for 2 seconds. For example, if ‘1 – 2’ appeared, participants repeated ‘one, two’. We instructed participants to start repeating these two numbers aloud immediately at a rate slightly faster than one digit per second, and to continue to repeat it during a blank screen for 2 seconds, to minimize potential interference created by initiating the suppression while encoding the memory items. Participants were instructed to continue suppression until they had responded. The experimenter was present to make sure suppression was sustained. No participant was reminded to maintain suppression more than three times throughout the session.

## Results

We used a Bayes Factor ANOVA model-comparison analysis similar to that in Experiment 1, with Color Recall as the dependent variable, and suppression included as another factor in addition to Age, Trial Type, and Label-Ability. As in Experiment 1 we excluded trials with reaction times over 10 seconds (Color: 0.41 % of trials excluded from the younger adults, 0.50 % from the older. Shape: 1.02 % trials excluded from the young, 0.70 % from the older). Mean Color Recall accuracies for younger and older adults in the different conditions are presented in Table 4.

The Bayes factor analysis indicated ‘decisive’ evidence for retaining age in the model ( $1/B = 1.0 \times 10^3$ ), as the younger adults (proportion correct:  $M = .83$ ,  $SD = .27$ ) performed better than the older adults ( $M = .67$ ,  $SD = .33$ ). Overall, easy-to-label colors ( $M = .84$ ,  $SD = .26$ ) were better recalled than difficult-to-label ( $M = .65$ ,  $SD = .38$ ;  $1/B = 3.2 \times 10^{150}$ ). Color-only memory ( $M = .79$ ,  $SD = .29$ ) was better than memory for color when bound to shapes ( $M = .70$ ,  $SD = .32$ ;  $1/B = 2.7 \times 10^{29}$ ), and Suppression had less than a moderate effect on recall overall ( $1/B = 2.55$ ; without Suppression;  $M = .76$ ,  $SD = .30$ , with Suppression;  $M = .73$ ,  $SD = .31$ ). We found no evidence that that Suppression affected the age groups differently overall



(Suppression  $\times$  Age Group;  $1/B = 0.62$ ), ruling out the alternative explanation that older adults performance was generally more adversely affected by Suppression. Younger-adult performance in the easiest condition (no suppression, easy-to-label, single feature) might indicate near-ceiling performance by the majority (mean accuracy of .95). However, there was ‘decisive’ evidence for retaining the interaction between Suppression and Label-Ability ( $1/B = 4.2 \times 10^6$ ), such that Suppression reduced performance for easy-to-label colors, but had little effect on difficult-to-label colors (see Figure. 3). This fits with previous research suggesting that Suppression does not impair memory for difficult-to-label, abstract, visual stimuli (Luria, Sessa, Gotler, Jolicoeur, & Dell’Acqua, 2010; Morey & Cowan, 2004; 2005; Sense, Morey, Heathcote, Prince, & Morey, 2017).

These results did not strongly replicate results of Experiment 1, where older adults exhibited a feature-binding deficit for easy-to-label colors, but not for difficult-to-label colors. Here, there was no evidence for retaining Age Group  $\times$  Trial Type  $\times$  Label-Ability;  $1/B = 0.041$ , and anecdotal evidence against including the four-way interaction of Age Group  $\times$  Trial Type  $\times$  Label-Ability  $\times$  Suppression ( $1/B = 0.51$ ).

However, we replicated decisive evidence for the comparatively larger performance drop between easy-to-label and difficult-to-label colors observed for older adults in Experiment 1 ( $1/B = 8.5 \times 10^{11}$ ). There was some evidence suggesting that Suppression modulated this effect; evidence for retaining the Age Group  $\times$  Suppression  $\times$  Label-Ability interaction ( $1/B = 2.96$ ), (see Figure 3). However, the evidence regarding this differential impact of Suppression was rather weak: although BFs close to 3 are often interpreted as ‘substantial’ (Jeffreys, 1961) this practice is problematic (see Morey, 2015). To follow up on this inconclusive three-way interaction, we looked at the data without Suppression, where evidence for retaining the Age Group  $\times$  Label-ability interaction was ‘decisive’ ( $1/B = 1.7 \times 10^{11}$ ). In comparison, for trials with Suppression, it was comparatively smaller (Age Group  $\times$

Label-Ability:  $1/B = 7.7$ ). This suggests that Suppression did impair the older adults comparatively more for the easy-to-label colors, suggesting that their memory performance was more reliant on sub-vocal rehearsal. However, given the rather weak evidence for retaining the three-way interaction - and potential concerns about near-ceiling performance by younger adults in the easiest condition - this requires replication with a larger sample. See Table 8 for the complete analysis output.

## Discussion

We replicated the key findings from Experiment 1: Younger adults performed better than older adults overall, and easy-to-label colors were better-remembered than difficult-to-label colors, overall. Importantly, we again found ‘decisive’ evidence ( $1/B = 8.53 \times 10^{10}$ ) that the performance drop between easy- and difficult-to-label colors was larger for the older adults. Crucially, while Suppression had a strong negative effect on memory for the easy-to-label colors it did not impair performance for the difficult-to-label colors in either age group. The specific impairment of Suppression on memory for easy-to-label colors provided an important manipulation check, because it suggested that participants used verbal labels for our intended easy-to-label colors, but not the difficult-to-label ones. The differential effect of Suppression on easy and difficult-to-label colors appeared bigger for older adults (see Figure 3, however the statistical evidence may be considered ‘inconclusive’;  $1/B = 2.96$ ).

In contrast to Experiment 1, these results did not strongly support our hypothesis that older adults’ reliance on verbal rehearsal produces the appearance of feature-binding deficits.  $B$  for including the four-way interaction (Age Group  $\times$  Trial Type  $\times$  Label-Ability  $\times$  Suppression) was close to 1. Hence, our data did not provide strong evidence either for accepting or rejecting our prediction that older adults would be comparatively more impaired for single-feature easy-to-label colors under suppression. Thus, replication with more

participants or trials is required to test this hypothesis adequately. However, the older adults in the second experiment performed a bit better in the binding condition than those in the first one. Perhaps suppression made verbal rehearsal more salient so that older adults attempted to apply it in the binding as well as the color-only condition, despite our prediction that rehearsal would be less effective for the bound condition. This merits further investigation in future studies.

However, we found that older-adult performance differed much more between difficult-to-label and easy-to-label colors than did younger-adult performance, replicating the strong evidence observed in Experiment 1. This effect was a lot weaker during concurrent suppression, but not completely abolished. Thus, our hypothesis that the older adults' benefit for easy-to-label colors was due to sub-vocal rehearsal was partially supported (see Figure 3). These results indicate that older adults appeared to benefit greatly from easy-to-label colors. Sub-vocal rehearsal appeared to play a role in driving this benefit, but may not be the only explanation, suggesting that other aspects of color 'commonness' may also benefit older adults, or that suppression does not completely prevent rehearsal. However, these results failed to provide clear indications regarding whether this influenced performance on single or binding trials differently in the two age groups.

### Experiment 3

Following two experiments providing decisive evidence for a comparatively larger performance gap between easy-to-label and difficult-to-label colors in older adults, we investigated why a similar effect was not observed for shapes in Experiment 1. In Experiment 3, we examined the possibility that the shapes might have been presented too briefly for older participants to generate the shape labels, in line with evidence that reduced processing speed

1 contributes to older adults' reduced visual WM capacity (Brown, Brockmole, Gow, & Deary,  
2 2012), especially when required to remember multiple objects (Guest, Howard, Brown, &  
3 Gleeson, 2015). If so, longer encoding time should result in similar observations for shapes to  
4 those observed for colors in Experiments 1 and 2. We included Suppression to test whether it  
5 would eliminate any effects of Label-Ability, thus suggesting they might be due to sub-vocal  
6 rehearsal. Hence Experiment 3 was identical to Experiment 2, except that Shape Recall was  
7 the dependent variable and the stimulus presentation time was 2500 ms for older adults (this  
8 encoding duration did not result in ceiling performance for single shape memory in older  
9 adults at set size three; Rhodes, Parra, & Logie, 2015). Stimulus presentation was 1500 ms  
10 for younger adults to avoid ceiling-level performance.

## 11 12 **Methods**

13 **Participants.** We recruited 52 new participants. Two older adults were excluded (one  
14 due to not understanding the task, one due to color-vision deficiency; 8 errors). The final  
15 sample consisted of 25 younger adults (8 male) aged 18 – 24 ( $M = 20.1$ ,  $SD = 1.8$ ) years, and  
16 25 older adults (8 male), aged 62 – 77 ( $M = 69.4$ ,  $SD = 4.7$ ) years. The older adults had  $M =$   
17  $15.8$ ,  $SD = 3.8$  years of education, the younger adults  $M = 14.7$ ,  $SD = 1.8$  years, which did not  
18 differ significantly between the groups  $t(30.26) = 1.24$ ,  $p = .23$ . Three younger and three  
19 older adults did not provide years of education. All older adults completed the ACE-III mini  
20 at the very end of the testing session, and no older adult was excluded based on the  
21 recommended cut-off score of 25 (Hsieh et al., 2015;  $M = 28.8$ ,  $SD = 1.6$ ). NART-predicted  
22 verbal IQ scores were significantly higher in the older group ( $M = 123.4$ ,  $SD = 3.5$ ) than the  
23 younger group ( $M = 114.5$ ,  $SD = 3.5$ ),  $t(48) = 8.89$ ,  $p < .001$ ,  $d = .59$ . The study was approved  
24 by our local Ethics Committee.

**Stimulus and Apparatus.** The stimuli were identical to those used in Experiments 1 and 2, displayed using the same equipment.

**Design and Procedure.** The procedure was identical to that used in Experiment 2, except that presentation time for older adults was 2500 ms but 1500 ms for younger adults. No participant was reminded to maintain suppression more than twice throughout the session, thus rendering it unlikely to have impacted performance. As in the previous experiment, there were four blocks of 58 trials (total 232 trials): 1. Shape-only, 2. Shape-only with Suppression, 3. Binding, 4. Binding with Suppression.

## Results

We used the same Bayes Factor ANOVA model-comparison analysis as in Experiment 2, with Shape Recall as the dependent variable, and Age, Trial Type, Label-Ability and Suppression as the factors of interest. We excluded trials with reaction times over 10 seconds (Color: 0.19% of trials excluded from the younger adults, 0.19% from the old. Shape: 0.33% trials excluded from the young, 1.22% from the old). Mean Shape Recall accuracies for younger and older in the different conditions are presented in Table 5.

Younger adults performed slightly better ( $M = .73$ ,  $SD = .31$ ) than older adults ( $M = .63$ ,  $SD = .34$ ;  $1/B = 1.67$ ), despite older adults' longer stimulus presentation time. We observed strong effects of binding condition, such that shape only ( $M = .73$ ,  $SD = .31$ ) was better than shape when also remembering color ( $M = .63$ ,  $SD = .34$ ;  $1/B = 1.0 \times 10^{32}$ ) and Label-Ability (easy-to-label shapes:  $M = .76$ ,  $SD = .30$ , difficult-to-label shapes:  $M = .60$ ,  $SD = .35$ ;  $1/B = 1.5 \times 10^{88}$ ), but not of Suppression (without Suppression:  $M = .69$ ,  $SD = .33$ , with Suppression:  $M = .67$ ,  $SD = .33$ ;  $1/B = 0.54$ ). Unexpectedly, there was no evidence for interaction between Label-Ability and Suppression ( $1/B = .03$ ). A large age-related binding

deficit appeared ( $1/B = 399.69$ ), but we found no clear evidence that this age-related binding deficit was modified by Label-Ability ( $1/B = 0.18$ ), or by Suppression ( $1/B = 0.05$ ). However, there was evidence for overall interaction between age group and Label-Ability ( $1/B = 6.32$ ).

These interactions should be interpreted with caution because younger and older participants performed slightly different tasks due to the difference in encoding time. Therefore, to follow up on the effects of Label-Ability and binding in the different age groups, we also analyzed them separately. For the younger adults, the effect of binding did not differ with Label-Ability ( $1/B = 0.05$ ), but for older adults, there was an interaction between label-ability and binding ( $1/B = 4.31$ ), such that there was a larger binding deficit for the easy-to-label shapes (similar to Experiment 1). Hence, by extending the stimulus presentation time for older adults, we produced an apparent feature-binding deficit for older adults for easy-to-label shapes but not for difficult-to-label shapes (see Figure 4), similar to the results for color memory in Experiment 1. However, Suppression did not appear to reduce this binding deficit in the older adults (Suppression  $\times$  Trial Type  $\times$  Label-Ability:  $1/B = 0.10$ ), undermining the inference that verbal rehearsal was the reason for the relatively good performance when shapes were easy to label. See Table 9 for the complete analysis output.

## Discussion

These results were consistent with the idea that, given sufficient encoding time, older adults' recall for single, easy-to-label shapes can benefit, creating an apparent binding deficit for such trials compared to younger adults (similar to results for color memory in Experiment 1). This indicated that this effect was not color-specific. However, curiously, suppression did not modify this effect for shapes, or affect either older or younger adults' recall, regardless of stimulus label-ability. This implied that the relatively good recall for easy-to-label shapes was not due to sub-vocal rehearsal of shape labels, unless the extended encoding time for older

adults enabled some verbal labeling despite concurrent suppression. Hence, although the results of Experiment 2 suggested that sub-vocal rehearsal contributed to the older adults' better recall for label-able colors, the results of Experiment 3 indicated that rehearsal did not play a similar role for shape memory.

Performance for label-able stimuli was better than that for less-label-able stimuli, both with and without suppression in both experiments. This suggested that either some sub-vocal rehearsal was still possible despite suppression, or that label-able features were better remembered for other reasons. Older adults may have been able to benefit comparatively more from easy-to-label single shapes than younger adults when given sufficient time to encode them. Instead of being driven by sub-vocal label rehearsal, some other feature of those easy-to-label, common shapes – perhaps that they were more familiar and/or easier to process – seems to have driven this benefit. Even though Brockmole, Parra, Della Sala, and Logie (2008) found no differences in discriminability of the difficult-to-label shapes (identical to those in our experiments) in younger and older adults in a preliminary search task, it is likely that the difficult-to-label shapes were more visually complex than the easy-to-label ones, which might for instance increase visual search rate (Alvarez & Cavanagh, 2004; Eng, Chen, & Jiang, 2005). Therefore, differences between easy- and difficult-to-label shapes in our study may have been driven by perceptual differences.

## General Discussion

We observed that while, overall, participants of both age groups remembered label-able stimuli better than less label-able, impairment for difficult-to-label stimuli appeared to be exacerbated in older adults. This was replicated in two experiments for color memory but only observed for single-item shape memory when older adults were given extra time to

1 encode items. Hence, while visual working memory was impaired with age, something about  
2 the label-able colors allowed older adults to overcome this deficit partially, and perform more  
3 similarly to younger adults. These results were in line with recent findings suggesting that  
4 older adults can compensate for visuospatial declines by using strategies during encoding  
5 (e.g., Siegel & Castel, 2018). Our results also fit with the Scaffolding Theory of Aging (Park  
6 & Reuter-Lorenz, 2009), suggesting that older adults may employ compensatory recruitment  
7 such as relying on more active strategies that draw in other brain regions to compensate for  
8 deteriorating visual memory with age. This compensatory recruitment is not necessarily  
9 associated with improved visual task performance (Reuter-Lorenz, Stanczak, & Miller,  
10 1999). However, in our study we observed substantial performance differences in an  
11 otherwise identical visual task simply by manipulating how easily colors could be labeled,  
12 indicating that in some circumstances, older adults can successfully compensate for declining  
13 visuospatial memory.

14         However, it is not clear by which mechanism the compensation we observed  
15 occurred. Our original hypothesis was that relatively better performance for easy-to-label  
16 items in older adults would be due to greater reliance on verbal encoding and rehearsal of  
17 labels for visual stimuli, considering that verbal WM is comparatively intact with age (see  
18 Jonides et al., 1996 for a review). The results of Experiment 2 (suppression impaired older  
19 adults' performance for easy-to-label colors, but had no effect on difficult-to-label colors, see  
20 Figure. 3) supported the hypothesis that compensation depended at least partly on strategic  
21 sub-vocal rehearsal. However, there was no effect of suppression on easy-to-label shape  
22 memory in Experiment 3. It is possible that suppression blocked some verbal rehearsal but  
23 not all. Even in studies with verbally presented material, suppression does not completely  
24 demolish all memory traces, which might explain why we did not observe a stronger effect.  
25 For shapes, the lack of effect of suppression in the older adults might be explained by the



1 extended stimulus presentation (2500 ms), which may have provided sufficient time for some  
2 labeling despite suppression. Finally, asking participants to perform Suppression arguably  
3 made the task more difficult, since it required performing an additional task. This might be  
4 extra detrimental in the more difficult task conditions, or for older adults. However,  
5 Suppression did not impair memory for difficult-to-label stimuli for either colors or shapes  
6 (see Exp. 2 and 3 respectively) in either age group, despite poorer overall memory for such  
7 stimuli. This suggested that the detrimental effect of Suppression (observed for easy-to-label  
8 colors) was because it prevented verbal rehearsal, rather than merely making the task more  
9 difficult.

10 In all three experiments, older adults had significantly higher predicted verbal IQ  
11 scores, measured using the NART (National Adult Reading Test), in line with research  
12 suggesting relatively intact verbal abilities with age but also potentially indicating higher  
13 peak-adult general cognitive abilities. These higher predicted verbal IQ scores could also  
14 suggest that the older adults may not have been as representative of the general population as  
15 the younger adults. Despite similar levels of reported education in younger and older adults,  
16 reaching that level of education was quite a bit less common in the older adults' generation,  
17 reinforcing this possibility. Moreover, we analyzed naming data and found that older adults  
18 were better able to provide names for the difficult-to-label colors and shapes than the younger  
19 adults (see Supplementary Materials). Hence, we can rule out the important potential  
20 alternative explanation for older adults' relative impairment for difficult-to-label colors: that  
21 they were less able to label uncommon stimuli than younger adults. However, their higher  
22 verbal IQ scores introduced another potential explanation for their overall performance.

23 However, based on the unclear evidence regarding the role of sub-vocal rehearsal we  
24 also consider additional processes which may contribute to this strong boost in memory for  
25 easy-to-label features in older adults. First, it is possible that our set of easy-to-label colors

1 was better remembered by older adults because such colors are easier to distinguish during  
2 encoding, as they can be readily and even possibly automatically categorized. For instance,  
3 some case-study evidence has suggested that maintenance of color categories does not rely on  
4 language. For example, Haslam, Wills, Haslam, Kay, Baron, and McNab (2007) described a  
5 patient with semantic dementia who was able to categorize different colors consistently,  
6 despite a near-complete loss of color language. Categorizing colors may depend on basic  
7 perceptual features, separate from verbal labels (Haslam et al., 2007). The universality of the  
8 basic color categories in most human languages also supports this. Although an effort was  
9 made to ensure the average luminance of the two color sets was relatively similar (see  
10 Supplementary Materials) other perceptual differences between our easy and difficult-to-label  
11 colors cannot be ruled out. However, the large performance reduction associated with  
12 suppression specifically for easy-to-label colors in Experiment 2 (regardless of age group),  
13 was consistent with the idea that verbal rehearsal does play a role, and that perceptual  
14 differences do not provide the whole explanation.

15       Second, visual memory for difficult-to-label information may be limited because it  
16 affords less opportunity to activate long-term memory representations. Souza and Skóra  
17 (2017) found that labeling colors (overtly or sub-vocally) improved younger-adult memory  
18 performance by activating long-term memory representations, rather than simply by adding  
19 verbal memory traces. If older adults' memory for easy-to-label colors was also  
20 comparatively 'boosted' because such colors automatically activated lexical, semantic  
21 representations that helped compensate visual memory, this would explain why this special  
22 benefit for easy-to-label colors in older adults was not completely abolished under  
23 suppression. For instance, while suppression strongly disrupts memory for individual letters –  
24 thought to rely on a phonological code – in younger adults (Chein & Fiez, 2010, Toppino &  
25 Pisegna, 2005), it does not seem to disrupt memory for words (Souza & Oberauer, 2018).

Olsson and Poom (2005) proposed that ‘pure’ visual memory relies on what can be held in the focus of attention (central to some models of WM; see Cowan et al., 2005; Oberauer, 2013), after observing that memory was much poorer for objects that did not belong clearly to different categories, such as ovals with varying aspect ratios and color mixtures along the natural boundaries of established color labels, compared to easy-to-categorize objects such as a red square. While their participants could remember a mean of 2.5 easily categorized objects, for objects without a clear category they had an average memory capacity of one item. They suggested that if an initially-presented object does not belong to a clear category and attention is directed to a new object, the initially-presented one is overwritten, leaving memory capacity of one item. Similar perceptual ‘overwriting’ processes have been observed in other studies (Enns & Di Lollo, 2000; Lakha & Wright, 2004, see also Logie, 1995; Phillips & Christie, 1977; Wilson, Scott, & Power, 1987). Furthermore, complex recognizable items were associated both with better memory precision and appeared supported by a richer range of neural representations than unrecognizable objects, suggesting that recognizable objects evoked richer and more variable contextual associations (Veldsman, Mitchell, & Cusack, 2017).

In our study, the larger age-related deficit for difficult-to-label colors was consistent with the established finding that ‘pure’ visual WM is impaired in old age (e.g., Johnson et al., 2010), but indicated that older adults can benefit significantly when opportunities for either verbal or semantic representations are available (easy-to-label colors). This supported theories about compensatory memory strategies in older adults (Logie, 2018; Park & Reuter-Lorenz, 2009), and might have implications for numerous memory phenomena. For instance, age-related dual-task deficits (see Jaroslawska & Rhodes, 2018 for a review) may be greater if the secondary task disrupts such strategies. These results also added to evidence that older adults generally benefit from opportunity for elaboration, i.e., strengthening memory traces

by adding more information (Kitagami, 2000; Osaka, Otsuka, & Osaka, 2012), and benefit proportionally more than younger adults when to-be-remembered information is consistent with past experience (Hess & Slaughter, 1990). Since we used a limited stimulus set in the present study it is possible that participants were able to generate a LTM entry for difficult-to-label stimuli throughout the study – future studies should consider this possibility. We now discuss the implications of using easy- or difficult-to-label stimuli when investigating age-related feature-binding deficits.

In Experiment 1, when colors were easy to label, older adults' performance was comparable to that of younger adults in the single-feature condition, suggesting they may have successfully used sub-vocal rehearsal to compensate for age-related declines in visual memory. Because their performance was poorer in the binding condition, this appeared as a visual feature-binding deficit. Hence, it is possible that some previous findings of age-related binding deficits observed using reconstruction paradigms may be explained similarly – perhaps deficits would not have been found if verbal strategies had been prevented. Specifically, conditions in several studies where age-related binding deficits were observed were similar to ours; they used easy-to-label stimuli, and did not impede verbal strategies (e.g., Brockmole & Logie, 2013; see Table 1 for an overview). Similarly, these results may fit with early evidence indicating older-adult memory deficits for locations, as well as bindings between common objects and colors (Chalfonte & Johnson, 1996). While Chalfonte and Johnson's paradigm differed from ours – their participants studied 30 to-be-remembered objects for 90 seconds – older adults appeared comparatively more impaired for information that was difficult to verbalize (i.e., locations and bindings between features).

In the present study, the younger adults in Exp. 2 performed at near-ceiling level in the easy-to-label, color-only condition (proportion correct: .95). Near-ceiling performance might explain the Age Group  $\times$  Label-ability interaction (i.e., why the difference between

1 easy- and difficult-to-label colors was smaller for younger than for older adults). However,  
2 this interaction was also observed in Exp. 1 (where younger adults performed further from  
3 ceiling; .92), suggesting that near-ceiling performance alone did not cause this interaction.  
4 Younger adults performing close to ceiling (over .95 proportion correct) in some conditions  
5 has been observed both in studies where older adults were found to have a binding deficit  
6 (e.g., Brown & Brockmole, 2010, Exp. 2; Chalfonte & Johnson, 1996), and where they did  
7 not (e.g., Brown & Brockmole, 2010, Exp. 1; Rhodes et al., 2016). Nevertheless, the role of  
8 ceiling effects in younger adults should be considered when measuring feature-binding  
9 deficits.

10 We initially hypothesized better performance in the single feature condition because  
11 three single features can be verbalized twice as fast as three bound features. However, the  
12 alternative explanation that older adults' performance benefits from easy-to-label colors  
13 because they enable activation of semantic representations may produce a similar pattern of  
14 results. While common features like 'green' (or 'circle'), should have accessible semantic  
15 representations, arbitrary *combinations* of common features in the binding condition, e.g.,  
16 'green circle' would likely have less accessible, or at least less rapid and/or routinely familiar  
17 semantic representations.

18 The results of our three experiments suggested that older adults' better performance  
19 for easy-to-label stimuli was because such stimuli enabled both sub-vocal rehearsal and  
20 activation of semantic representations. Particularly, puzzling differences between how the  
21 opportunity to label influenced memory for color and shapes, respectively, suggested that the  
22 type of feature measured might also play a complex role. Visual complexity differences  
23 between easy- and difficult-to-name shapes may have been a confounding factor, and future  
24 research exploring the potential contribution of such perceptual differences on memory  
25 performance in younger and older adults would be informative. Still, our findings strongly

1 indicated that reconstruction paradigms with easy-to-label stimuli should be used with  
2 caution, as they may introduce strategy-related confounds between age groups. For instance,  
3 this might explain discrepancies in recently developed delayed-estimation precision  
4 paradigms, where an age-related mis-binding deficit was observed for colored bars (Peich,  
5 Husain, & Bays, 2013), but not for the location of complex fractals (Pertzov, Heider, Liang,  
6 & Husain, 2015). Such paradigms quantify feature-binding deficits via mis-binding errors,  
7 i.e., incorrectly reporting a feature that was part of the memory array, but was not the target  
8 item. In the present study, we did not analyze the proportion of in-array errors due to the  
9 small number of errors in some conditions. However, it appeared that more such errors were  
10 made for easy- than for difficult-to-label colors, while no clear pattern appeared for shapes  
11 (see Supplementary Materials). This suggests that verbalization might also contribute to mis-  
12 binding errors.

13 Different types of binding tasks may draw on different cognitive processes (e.g.,  
14 Delvenne & Bruyer, 2004; Ecker et al., 2013; Shimi & Logie, 2018; Wheeler & Treisman,  
15 2002). Some include location as a feature, others as a cue to probe items, others simply as  
16 what inherently binds features into an object (see Kovacs & Harris, 2019 for discussion on  
17 how separate visual features become integrated objects via a mutual location). Older adults  
18 may struggle specifically with binding items to locations, more than remembering which  
19 items were present (Thomas, Bonura, Taylor, & Brunyé, 2012). This might exacerbate  
20 binding deficits in some paradigms. The extent to which change detection, reconstruction and  
21 delayed estimation (misbinding) paradigms measure the same binding process is  
22 controversial – and beyond the scope of this paper. However, all visual *conjunctive bindings*  
23 (i.e., surface feature bindings, such as shape and color) are by definition created by features  
24 coinciding in space (but see studies comparing such conjunctive bindings with *relational*  
25 *bindings*, i.e., a shape and a colored blob presented side by side but joined by an arrow. Van

Geldorp, Parra, and Kessels, 2015 found that healthy aging affected both these types of binding similarly). While we only used one type of paradigm here, our results added to this debate by highlighting that some discrepancies in the literature may depend on whether stimuli in the single-feature condition allow and/or facilitate activation of additional verbal and/or semantic representations. The usefulness of such representations may vary depending on how feature memory is probed, and it is unclear whether similar effects would be observed using change detection or other paradigms. For instance, Sense, Morey, Prince, Heathcote, and Morey (2017) observed that verbalization did not improve visual change detection performance in younger adults.

Simple feature-binding tests may help distinguish healthy from pathological aging, although there is some debate regarding which type of paradigm to use (see Liang et al., 2016; Parra et al., 2016). Pathological aging is identified by comparing patient binding deficits to those observed in healthy aging, and it is therefore important that paradigms not produce ‘false’ visual binding deficits in the healthy comparison group. Correspondingly, pathological binding-deficits observed in paradigms with easy-to-label, common stimuli could reflect greater patient reliance on either verbal rehearsal or semantic representations boosting visual single-feature performance – processes which are less efficient in the binding condition. This should be carefully distinguished from visual feature-binding memory deficits.

Taken together, our results suggested that to ensure that participant groups do not use different cognitive mechanisms in different experimental conditions (i.e., single-feature and binding conditions), using difficult-to-label, uncommon items – presumably more cumbersome to rehearse verbally – is a more reliable approach than blocking verbal rehearsal with suppression. Unexpectedly, participants appeared more likely to sub-vocally rehearse color than shape stimuli. These results highlighted the importance of considering differences

1 in spontaneous strategy use not just between younger and older adults, but also among the  
2 specific stimuli used. Experimental manipulations of stimulus label-ability and suppression  
3 may help detect patterns in such differences.

## 5 **Conclusion**

6 Our results fit with previous evidence indicating that visual memory for non-  
7 categorical information is very limited (e.g., to only one item; Olsson & Poom, 2005), likely  
8 because it is more difficult to engage other systems, such as verbal WM or long-term  
9 memory. Crucially, our results showed that older participants were more adversely affected  
10 by difficult-to-label colors, indicating an increased reliance on rehearsal of verbal labels or  
11 other types of elaboration to maintain visually presented stimuli with age. This possibility  
12 should be considered when designing future memory studies because age-related visual  
13 memory decline may be more accurately captured when such elaboration is prevented. This  
14 has interesting implications for the wider visual WM literature beyond feature-binding, as it  
15 suggests that comparing younger- and older-adult task performance may not  
16 straightforwardly reveal the age-related decline in visual WM, but instead applications of  
17 different strategies that tap different cognitive mechanisms, to varying degrees (for a  
18 discussion see Logie, 2018).

19 We found some evidence that differential application of verbal strategies or  
20 opportunity for activation of semantic representations might account for some of the  
21 literature's inconsistencies regarding age-related feature-binding deficits. This highlighted  
22 that observing binding 'deficits', depending as it does on statistical differences in differences,  
23 may also depend on many experimental and sampling parameters. These include participant  
24 tendency and ability to label stimuli and procedural availability to rehearse labels, which may  
25 transact in creating required statistical interactions (i.e., binding deficits). Identifying and



1 understanding the roles of procedure and participant characteristics in this could also be  
2 useful in establishing appropriate experimental paradigms for using healthy older adults as  
3 controls to identify symptoms of pathological aging (e.g., Parra et al., 2009a).

4 More broadly, our results highlighted how stimuli that can easily be labeled or  
5 categorized may have qualitatively different effects on participants of different age groups,  
6 and stressed the importance of considering the interplay between visual and verbal memory  
7 (Souza & Skóra, 2017), and the importance of considering alternative strategies that may be  
8 used for performing the same task (Logie, 2018) both of which appear crucial for  
9 understanding how older adults perform every day – as well as experimental – cognitive  
10 tasks.

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Table 1.

*Overview of previous studies on age-related feature-binding deficits.*

Study	Stimulus Type	Set Size	Suppression	Binding Paradigm	Encoding	Retention	Age-related deficit
Brockmole, Parra, Della Sala & Logie, 2008							
Exp. 1	Common shapes and colors	2,4 or 6	Yes	Change Detection	753 ms	906 ms	No
Exp. 2	Difficult-to-name shapes and colors	4	No	Change Detection	1000 ms	906 ms	No
Exp. 3	Common shapes and colors	6	Yes	Reconstruction task with location cue	753 ms	1 or 5 sec	No
Read, Rogers, & Wilson, 2016							
Exp. 1.	Common colored squares in certain locations.	4	No	Change Detection	500 / 2000 ms (simultaneous / sequential)	900 ms	No
Exp. 2.	Common shapes in colors, at certain locations.	3	No	Change Detection	500 ms (simultaneous)	900 ms	No
Rhodes, Parra & Logie, 2015	Common shapes and colors	3	Yes	Change Detection	900 or 2500 ms	1000 ms	No
Parra, Abrahams, Logie & Della Sala, 2009b							
Exp. 1	Objects constructed using object shapes, defined by a figure and ground area, filled with non-basic colors.	3	No	Change Detection (say same or different)	2000 ms	900 ms	No
Exp. 2	Same	4	No	Change Detection (say same or different)	1000 ms	900 ms	No
Pertzov, Heider, Liang, & Husain, 2015	Complex fractals	1 or 3	No	Reconstruction; select target and drag to its original location: misbinding errors calculated by rate of "swap errors"	1 or 3 sec	1 or 4 seconds	No
Brown et al., 2017							
Exp. 1	Common shapes and colors	3	Yes	Change Detection (one probe)	900 ms or 1500 ms	1000 ms	No
Exp. 2	Common shapes and colors	3	Yes	Change Detection (one probe)	500 ms/item (sequential presentation of 3 items)	1000 ms	No
Exp. 3	Common shapes and colors	3	Yes	Change Detection (one probe)	900ms	1000 ms (including suffix distractor)	Yes

Brown & Brockmole, 2010							
Exp. 1	Common colors and shapes	3	Yes	Change detection (one probe)	900 ms	1000 ms	No
Exp. 2							
	Common colors and shapes	3	Yes	Change detection (one probe)	1500 (ms)	1000 ms	Yes
Kinjo, 2010							
Exp. 1	Cards with common colors, shape, and numbers.	1,2 or 3 cards	No	Change detection	2000 ms	6000 ms	Yes (for 'binding' 2 and 3 features)
Exp. 2	Same	Same	No	Change detection	Self-paced encoding (maximum 2 minutes)	6000 ms	No (older adults could bind three features)
Killin, Abrahams, Parra, Della Sala, 2018							
	Uncommon shapes (same as in our study) and non-primary colors	3	No	Change Detection	2000 ms	900 ms	No
Cowan, Naveh-Benjamin, Kilb & Sauls, 2006							
Exp. 1a	Common colored-squares	4, 6, 8, or 10	No	Change Detection	250 ms	1000 ms	Yes
Exp. 2a	Same	Same	No	Same as above, but separate block for item and binding trials	250 ms	1000 ms	Yes (small)
Brockmole & Logie, 2013							
	Either common shapes or animals in common shapes.	1, 2,3 or 4	No	Reconstruction of objects by clicking on a color patch, then shape, and then location.	2 seconds per item (items shown simultaneously, if four items; total encoding = 8 seconds)	Immediate recall	Yes
Kessels, Hobbel, & Postma, 2007							
	Common objects presented in grid	7	No	Reconstruction of all items <i>Objects only, Positions only, Binding;</i> associate objects with the correct location.	3 seconds per item (sequential presentation)	Immediate recall	Yes
Peich, Husain, & Bays, 2013							
	Colored bars (continuous)	1 or 3	No	Reconstruction; Misbinding. Recreate targets' (continuous) color and orientation, probed by location. Feature-binding errors = incorrect report of color or orientation belonging to an item at un-probed location.	200 ms or 2000 ms	1000 ms (including 100 ms pattern mask)	Yes

Mitchell, Johnson, Raye, Mather & D'Esposito, 2000a Exp. 1	Common object drawing in different common colors	3	No	Change Detection (comparing object only, location only, or combination).	1000 ms per item (sequential presentation)	8000 ms	Yes
Mitchell & Cusack, 2018.	Locations and colors (continuous report using color-wheel)	1-4	No	Reconstruction (continuous). Mis-binding given by probability of responding for the non-target distribution.	250 ms	900 ms	Yes (modest)

- 1 *Note.* The binding test used in the Change Detection paradigm includes a probe display (or a
- 2 probe item), which is either identical to the original to-be-remembered display, or has
- 3 changed. Participants then indicate if the probe display is the same as the original display, or
- 4 different. To correctly identify a binding change, participants typically need to notice that two
- 5 features from the original display have been swapped around (e.g., a shape has taken the
- 6 color of a different shape).

Table 2

*Color accuracy (proportion correct) by age groups and experimental factors in Experiment*

*1.*

			Mean	SD
Younger	Single	Difficult	.79	.10
		Easy	.92	.08
	Binding	Difficult	.69	.12
		Easy	.86	.07
Older	Single	Difficult	.58	.08
		Easy	.90	.09
	Binding	Difficult	.51	.11
		Easy	.73	.09

1 *Note.* Difficult = Difficult-to-label; Easy = Easy-to-label.

Table 3

*Shape accuracy (proportion correct) by age groups and experimental factors in Experiment 1.*

			Mean	SD
Younger	Single	Difficult	.72	.10
		Easy	.90	.10
	Binding	Difficult	.66	.11
		Easy	.77	.09
Older	Single	Difficult	.54	.09
		Easy	.75	.11
	Binding	Difficult	.42	.13
		Easy	.56	.11

*Note.* Difficult = Difficult-to-label; Easy = Easy-to-label.



1

Table 4

*Color accuracy (proportion correct) by age groups and experimental factors in Experiment*

2.

With Suppression				
			Mean	SD
Younger	Single	Difficult	.80	.10
		Easy	.92	.08
	Binding	Difficult	.73	.12
		Easy	.84	.06
Older	Single	Difficult	.60	.10
		Easy	.77	.12
	Binding	Difficult	.50	.09
		Easy	.71	.09
Without Suppression				
Younger	Single	Difficult	.79	.08
		Easy	.95	.07
	Binding	Difficult	.69	.11
		Easy	.86	.07
Older	Single	Difficult	.57	.13
		Easy	.91	.12
	Binding	Difficult	.48	.09
		Easy	.78	.09

*Note.* Difficult = Difficult-to-label; Easy = Easy-to-label.

2

Table 5

*Shape accuracy (proportion correct) by age groups and experimental factors in Experiment 3.*

With Suppression				
			Mean	<i>SD</i>
Younger	Single	Difficult	.64	.11
		Easy	.85	.09
	Binding	Difficult	.61	.10
		Easy	.76	.09
Older	Single	Difficult	.60	.13
		Easy	.77	.10
	Binding	Difficult	.50	.12
		Easy	.62	.08
Without Suppression				
Younger	Single	Difficult	.68	.11
		Easy	.88	.10
	Binding	Difficult	.60	.13
		Easy	.81	.09
Older	Single	Difficult	.62	.09
		Easy	.81	.12
	Binding	Difficult	.52	.12
		Easy	.61	.12

*Note.* Difficult = Difficult-to-label; Easy = Easy-to-label.

1 Table 6  
 2 Results of Experiment 1 (Bayes Factor ANOVA for Color Memory).

	$B$	Error	$1/B$
Age Group $\times$ Trial Type $\times$ Label-Ability	0.078	$\pm 4.31\%$	12.82
Label-Ability $\times$ Trial Type	4.07	$\pm 4.04\%$	0.25
Age Group $\times$ Label-Ability	$4.3 \times 10^{-7}$	$\pm 4.52\%$	$2.33 \times 10^6$
Age Group $\times$ Trial Type	3.22	$\pm 4.43\%$	0.31
Label-Ability	$4.02 \times 10^{-99}$	$\pm 4.21\%$	$2.5 \times 10^{98}$
Trial Type	$7.20 \times 10^{-22}$	$\pm 4.06\%$	$1.4 \times 10^{21}$
Age Group	0.032	$\pm 3.97\%$	31.59

3 *Note.* In this Bayes Factor model comparison approach  $B$  represents strength of  
 4 evidence in favor of removing the main effect or interaction from the full model (including  
 5 all other main effects and interactions). So,  $B < 1$  indicates evidence that an omitted  
 6 parameter was important, while  $B > 1$  indicates evidence it was not.  $1/B$  provides evidence  
 7 for retaining the parameter in the model.

- 1 Table 7
- 2 Results of Experiment 1 (Bayes Factor ANOVA for Shape Memory).

	$B$	Error	$1/B$
Age Group $\times$ Trial Type $\times$ Label-Ability	18.43	$\pm 2.31\%$	0.054
Label-Ability $\times$ Trial Type	0.040	$\pm 2.4\%$	24.72
Age Group $\times$ Label-Ability	8.90	$\pm 3.02\%$	0.11
Age Group $\times$ Trial Type	1.12	$\pm 4.68\%$	0.90
Label-Ability	$2.8 \times 10^{-48}$	$\pm 3.14\%$	$3.6 \times 10^{47}$
Trial Type	$1.8 \times 10^{-31}$	$\pm 2.59\%$	$5.5 \times 10^{30}$
Age Group	0.0033	$\pm 3.57\%$	299.13

- 3 *Note.*  $1/B$  provides evidence for retaining the parameter in the model when greater than 1.

- 1 Table 8
- 2 Results of Experiment 2 (Bayes Factor ANOVA for Color Memory).

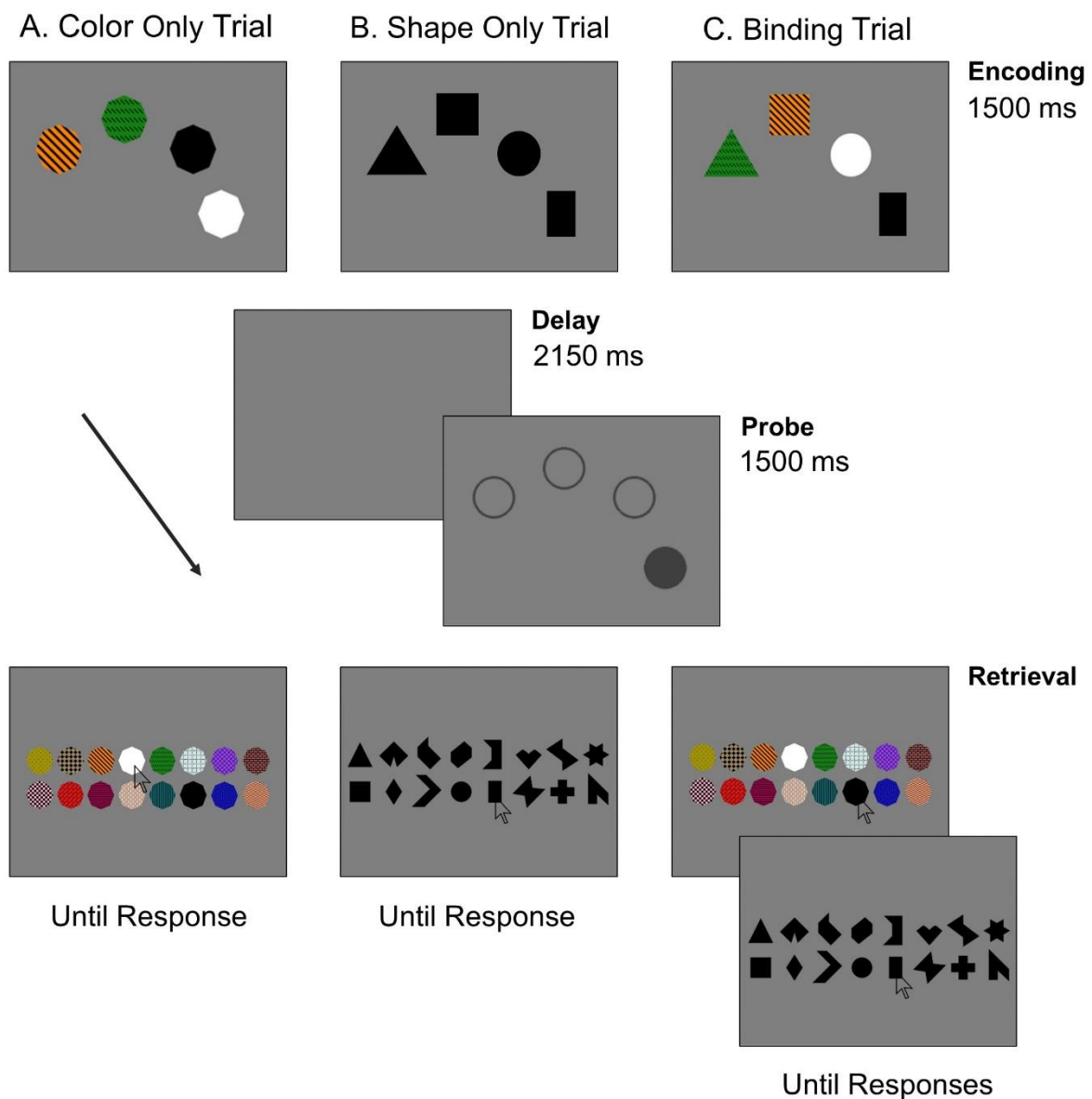
	$B$	Error	$1/B$
Age Group $\times$ AS $\times$ Trial Type $\times$ Label-Ability	1.98	$\pm 4.55\%$	0.51
AS $\times$ Trial Type $\times$ Label-Ability	11.0	$\pm 4.23\%$	0.091
Age Group $\times$ AS $\times$ Label-Ability	0.34	$\pm 4.32\%$	2.96
Age Group $\times$ Trial Type $\times$ Label-Ability	23.71	$\pm 4.91\%$	0.04
Age Group $\times$ AS $\times$ Trial Type	20.69	$\pm 4.5\%$	0.05
AS $\times$ Label-Ability	$2.40 \times 10^{-7}$	$\pm 4.4\%$	$4.2 \times 10^6$
Label-Ability $\times$ Trial Type	28.46	$\pm 4.41\%$	0.04
Age Group $\times$ Label-Ability	$1.2 \times 10^{-11}$	$\pm 5\%$	$8.53 \times 10^{10}$
AS $\times$ Trial Type	7.72	$\pm 4.51\%$	0.13
Age Group $\times$ AS	1.63	$\pm 4.84\%$	0.62
Age Group $\times$ Trial Type	25.06	$\pm 4.48\%$	0.04
Label-Ability	$3.11 \times 10^{-151}$	$\pm 4.7\%$	$3.2 \times 10^{150}$
AS	0.39	$\pm 4.4\%$	2.55
Trial Type	$3.7 \times 10^{-30}$	$\pm 4.55\%$	$2.7 \times 10^{29}$
Age Group	$9.9 \times 10^{-4}$	$\pm 4.87\%$	$1.0 \times 10^3$

- 3 *Note.*  $1/B$  provides evidence for retaining the parameter in the model when greater than 1. AS
- 4 = Articulatory Suppression.

- 1 Table 9
- 2 Results of Experiment 3 (Bayes Factor ANOVA for Shape Memory).

	<i>B</i>	Error	<i>1/B</i>
Age Group $\times$ AS $\times$ Trial Type $\times$ Label-Ability	3.97	$\pm 4.33\%$	0.25
AS $\times$ Trial Type $\times$ Label-Ability	26.46	$\pm 4.35\%$	0.038
Age Group $\times$ AS $\times$ Label-Ability	16.25	$\pm 3.79\%$	0.062
Age Group $\times$ Trial Type $\times$ Label-Ability	5.43	$\pm 3.64\%$	0.18
Age Group $\times$ AS $\times$ Trial Type	21.51	$\pm 4.38\%$	0.05
AS $\times$ Label-Ability	30.70	$\pm 3.81\%$	0.033
Label-Ability $\times$ Trial Type	0.80	$\pm 3.83\%$	1.25
Age Group $\times$ Label-Ability	0.16	$\pm 4.72\%$	6.32
AS $\times$ Trial Type	22.52	$\pm 3.72\%$	0.044
Age Group $\times$ AS	28.90	$\pm 3.8\%$	0.035
Age Group $\times$ Trial Type	0.0025	$\pm 4.04\%$	399.69
Label-Ability	$6.7 \times 10^{-89}$	$\pm 4.04\%$	$1.5 \times 10^{88}$
AS	1.85	$\pm 4\%$	0.54
Trial Type	$9.7 \times 10^{-33}$	$\pm 3.95\%$	$1.03 \times 10^{32}$
Age Group	0.60	$\pm 3.98\%$	1.67

- 3 *Note.*  $1/B$  provides evidence for retaining the parameter in the model when greater than 1. *AS*
- 4 = Articulatory Suppression.



1

2 *Figure 1.* Illustration of the trial sequence Experiment 1. A. *Color only trial.* Participants

3 remember colored blobs, and respond with a mouse-click from a selection of 16 color

4 options. B. *Shape only trial.* Participants remember black shapes. C. *Binding trial.*

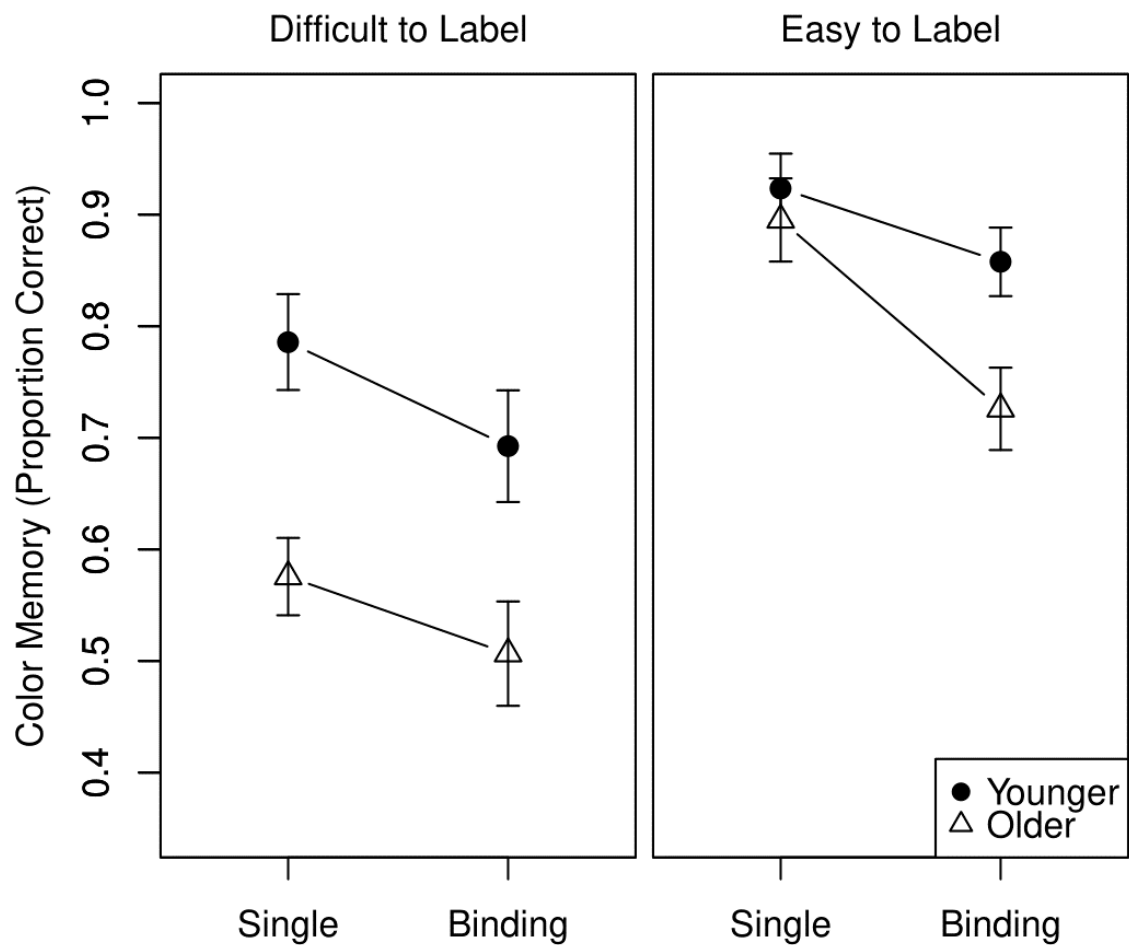
5 Participants see colored shapes, and need to remember both the color and shape of the probed

6 item. Participants did one binding block of trials where color was probed first (as illustrated),

7 and another block where shape was probed before color. Mouse cursors represents correct

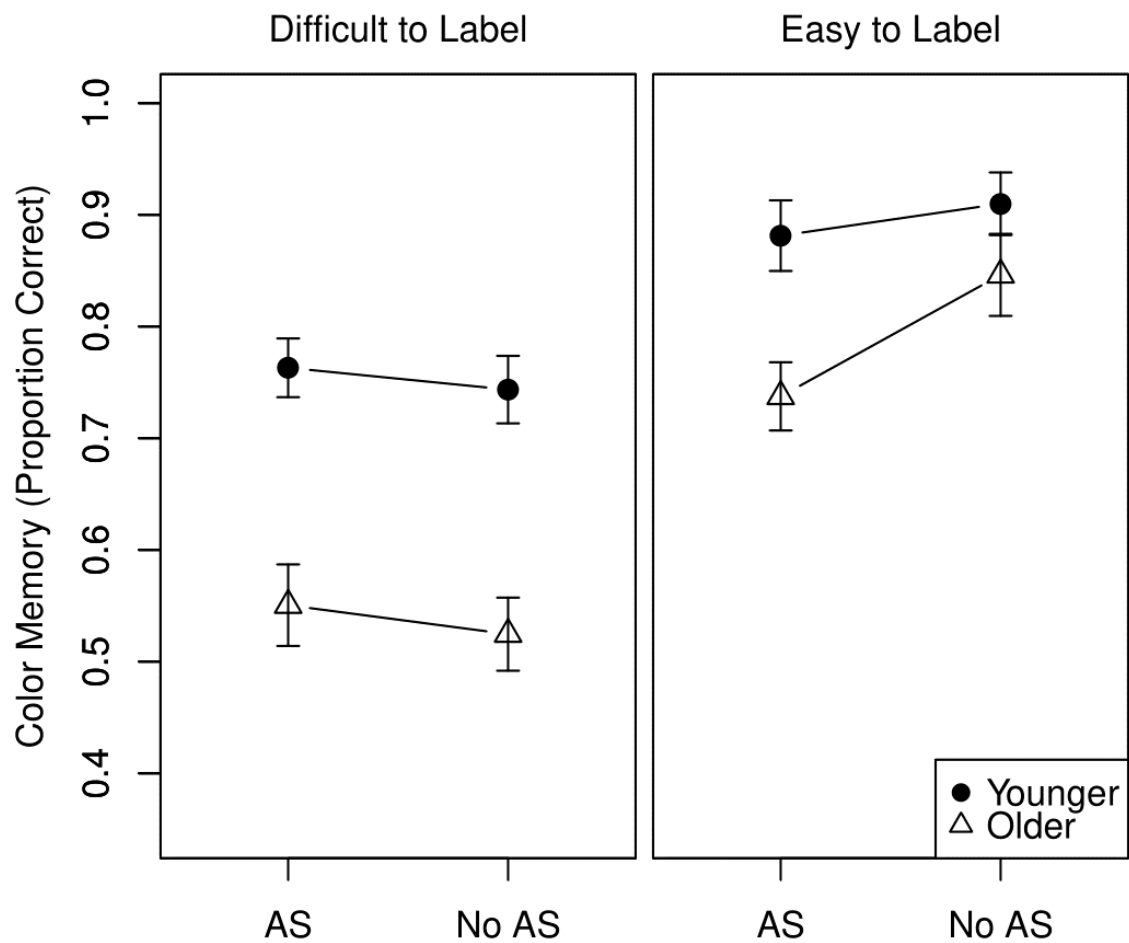
- 1 responses. Participants had unlimited time to respond. *Note.* Different fill patterns represent
- 2 different colors and items are not drawn to scale.
- 3





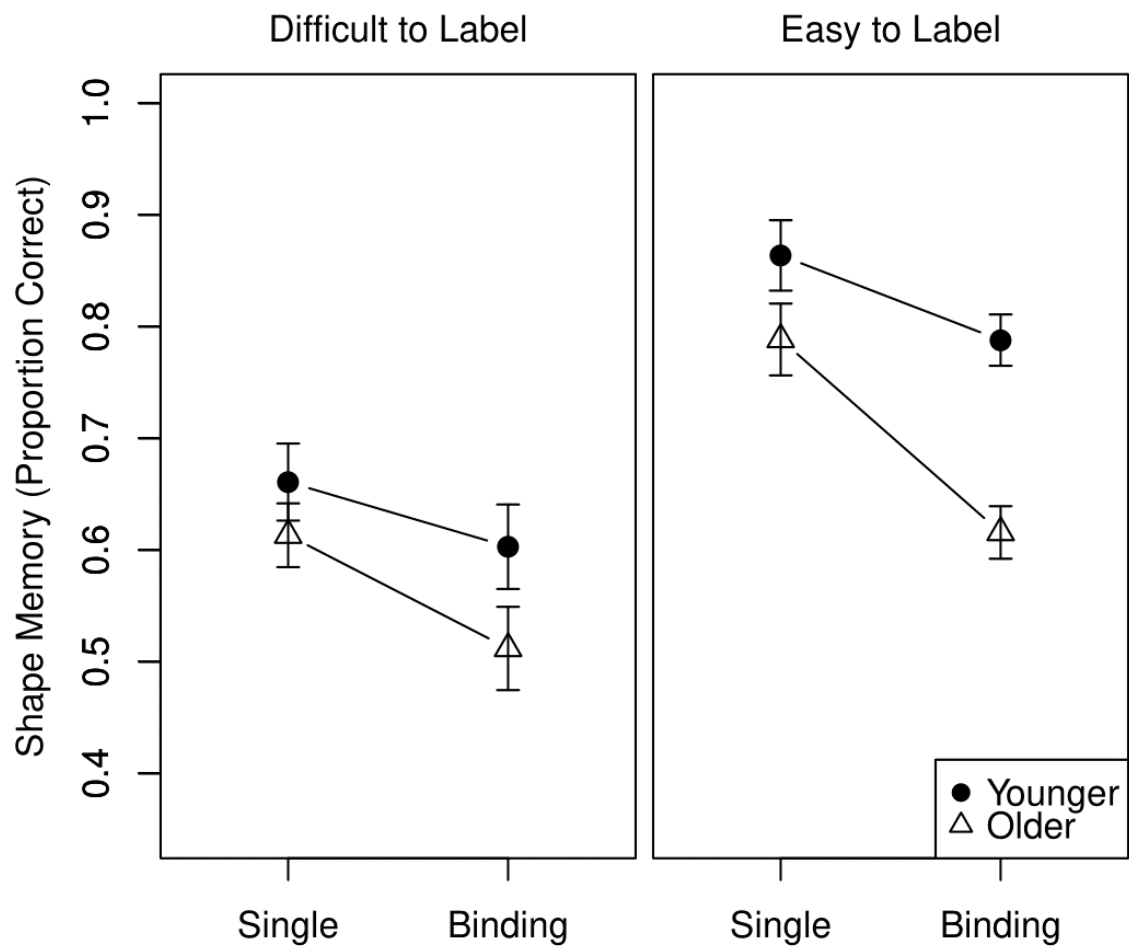
1

2 *Figure 2.* Color Memory Accuracy (Proportion correct) in Experiment 1, by Age Group,  
 3 Label-Ability and Binding condition. Error bars are within-subjects 95% confidence intervals,  
 4 adjusted values calculated using method from Morey (2008).



1

2 *Figure 3. Color Memory Accuracy (Proportion correct) in Experiment 2, by Age Group,*3 *Label-Ability and AS (Articulatory Suppression). Error bars are within-subjects 95%*4 *confidence intervals, adjusted values calculated using method from Morey (2008).*



1

2 *Figure 4.* Shape Memory Accuracy (proportion correct) in Experiment 3, by Age Group,

3 Label-Ability and Binding Condition. Error bars are within-subjects 95% confidence

4 intervals, adjusted values calculated using method from Morey (2008).